intensity profile of the fibre and waveguide modes, was found to be ~4.3 dB. The signal propagation losses can thus be estimated below 0.3 dB. This indicates that FEDW devices can be fabricated with scattering loss below 0.2 dB/cm. This is the first time that a high-quality mode profile and low propagation losses at 1.55 μm are reported in a waveguide written by femtosecond laser pulses.

Fig. 2 Experimental mode profile at 1.55 μm and Gaussian fit
Inset: Mode contour plot

Fig. 3 Waveguide test setup
OSA: optical spectrum analyser; WDM: waveguide division multiplexing

Fig. 4 Gain and enhancement against signal wavelength

Conclusions: We have demonstrated the first Er:Yb-doped active waveguide fabricated by femtosecond pulses exhibiting a singlemode at 1.5 μm with Gaussian circular profile, low scattering losses (<0.2 dB/cm) and 0.2 dB internal gain when used as an active element in a standard waveguide amplifier setup. Higher gain is expected from the optimisation of the writing process, the pumping setup and the dopant concentrations in the substrate. Lasing experiments using shorter waveguide lengths are in progress.

References

Injection-locked 1.55 μm VCSELs with enhanced spur-free dynamic range

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Injection locking is demonstrated to improve the analogue performance of long wavelength VCSELs. The third-harmonic spur-free dynamic range was improved by 9 dB/Hz1/2 to be 93 dB/Hz1/2, and the modulation bandwidth was increased two-fold.

Introduction: Injection locking of semiconductor lasers has been actively investigated recently [1,2]. The injection-locking phenomenon occurs when an injection source (master) laser is slightly detuned to frequencies lower than that of the injection-locked (slave) laser, and the injected power falls within a certain range relative to the slave laser. In this Letter, we demonstrate that the injection-locking technique can be used to enhance the analogue modulation performance of 1.55 μm VCSELs. A 9 dB/Hz1/2 improvement in spur-free dynamic range (SFDR) for third-harmonic distortion (from 84 to 93 dB/Hz1/2) was achieved at 1 GHz. This is the highest reported third-harmonic SFDR for 1.55 μm VCSELs. We also achieved a factor of 2 enhancement of resonance frequency (f0) with a flat modulation response below f0.

Background: In analogue systems, one of the most important figures-of-merit is the spur-free dynamic range (SFDR), defined as dynamic range at the point when the system noise floor equals the distortion noise. Distortion is typically measured on single-tone second- and third-order harmonics, as well as two-tone intermodulation products (IMD3). The distortion physically originates from the nonlinear characteristics of the laser, including nonlinearities of the light-current (LI) curve, the carrier-photon interaction or from spatial hole-burning [3]. SFDR is a strong function of frequency, and has its lowest value at frequencies near the relaxation oscillation frequency. Thus, lasers are typically analogue modulated at frequencies well below this frequency. The highest reported IMD3 SFDR for a distributed feedback (DFB) laser emitting at 1.3 μm is 100 dB/Hz1/2 for frequencies below 1 GHz.
Conversely, for a vertical cavity surface emitting laser (VCSEL) emitting at 850 nm, the highest IMD3 SFDR is 113 dB/Hz^{2/3} [5] at 0.9 GHz. The highest SFDR (third-harmonics) for a 1.55 μm VCSEL reported to date is only 81 dB/Hz^{2/3} at 1 GHz [6].

Optical injection locking has previously been used to improve SFDR. Using an external cavity tunable laser as the injection source, a 1.5 μm DFB laser was reported to exhibit a 5 dB/Hz^{2/3} improvement in SFDR, owing to a 15 dB/Hz^{2/3} reduction in IMD3 power. The resulting injection-locked DFB had a 100 dB/Hz^{2/3} SFDR at 2 GHz [7]. In this Letter, we report for the first time an improved SFDR in an injection-locked 1.55 μm VCSEL using a compact DFB laser as the master laser.

**Experimental setup:** Experiments were performed using 1.55 μm tunable VCSELs [8]. A commercially available DFB laser was used as the master laser in our injection locking experiments (see Fig. 1). A circulator (with angle-polished connectors) was used to couple the master laser light into the slave VCSEL. The modulated VCSEL signal from the third port of the circulator was coupled into a high-speed (10 GHz) detector, followed by a 20 GHz low-noise amplifier. An optical spectrum analyser was used for the harmonic distortion studies. Each RF power data point was averaged for approximately 1 min.

To achieve the locking conditions, the VCSEL was electrostatically tuned [8], whereas the DFB temperature was adjusted to vary the wavelength detuning. The DFB power was adjusted by varying the DC bias. The locking phenomenon typically occurs between 0 and +0.3 nm detuning, while the analogue improvement is typically observed in a smaller range (~0.05 nm detuning).

**Experimental results:** Fig. 2 shows the typical optical spectra for the injection-locking experiments. Measured at the output of the laser, the CW DFB optical spectrum (Fig. 2a) shows a sidemode suppression ratio of 43 dB. The optical spectrum for the free-running and injection-locked VCSEL (Fig. 2b) is measured at the output of the circulator. Fig. 2b shows that the VCSEL shifts from its free-running wavelength to lock onto the DFB wavelength at a slightly longer wavelength (right-hand side). When the slave laser is locked, an ~11 dB increase in optical power output is obtained for the VCSEL, mainly due to the reflection of the DFB laser light from the VCSEL and optics. The circulator output consists of both modulated VCSEL light as well as the CW DFB laser power.

Analogue modulation experiments were performed on a VCSEL with wavelength 1555.3 nm. An optimum injection condition was achieved when an estimated ~10 dBm optical power was injected into the slave VCSEL with the master laser wavelength at 0.19 nm longer than the VCSEL free-running wavelength. Fig. 3 shows the small signal modulation response of the VCSEL as measured by a network analyser, with ~30 dBm RF input signal. The 3 dB bandwidth for the free-running VCSEL is 2.7 GHz. This increases to 5 GHz when the VCSEL is injection locked, a nearly twofold improvement. Furthermore, the modulation response remains flat at lower frequencies. This is very desirable for high bandwidth data transmission and has not been observed in previous injection-locking reports, to the best of our knowledge. The RF gain at the fundamental frequency of 1 GHz increases by ~3 dB. This is the first demonstration of increased relaxation frequency and RF response in 1.55 μm VCSELs.

Fig. 4 shows the fundamental and third-harmonic power against RF input power for single-tone modulation at 1 GHz. The RF input power was attenuated in 1 dB increments, starting at 0 dBm. A 4 dB enhancement of the fundamental tone power and a 15 dB reduction in the third-harmonic distortion power were obtained with injection locking. With the system noise floor at ~120 dBm/Hz, the SFDR is determined to be 84 and 93 dB/Hz^{2/3} for the free-running and injection-locked cases, respectively. The enhancement of the fundamental tone and reduction of third-harmonic distortion are sensitive to the exact locking conditions and the single-tone RF frequency. However, the general trend of SFDR improvement is observed for several lasers.
Introduction: Photonic crystal (PC) [1, 2] planar cavities are likely to form compact building blocks, which can be used in future integrated nanophotonic systems. One of the most notable characteristics of PC cavities is that the mode profile and the quality (Q) factors are geometrically controlled and can be designed. Using simple defect cavity designs, the first photonic crystal laser crystals were reported [3] on InGaAsP multi-quantum well (MQW) structures several years ago. Quantum dot (QD)-PC lasers, however, have been more difficult to construct due to lower available gain from QD material [4, 5]. The smaller gain is not only due to a lower total volume of actively emitting material but also from variations in the spatial locality of QDs as well as inhomogeneous emission broadening. These effects result in a smaller number of QDs contributing to the gain in a resonance as the Q factor is increased.

Our approach to address these issues is to use high Q cavities with relatively larger mode volumes. In this Letter, we describe simple designs of coupled cavities in square lattice photonic crystals and demonstrate laser operation from such quantum dot photonic crystal (QD-PC) cavities.

Discussions: We start by using square lattice defect cavities since their predicted mode volumes are generally larger due to the smaller bandgap. To increase the mode volume we analyse coupled two-defect cavity structures with a three-dimensional finite difference time domain (3D-FDTD) model. The analysed two-defect cavities were located two lattice constants (a) apart from each other to form one coupled cavity mode in a two-dimensional (2D) square lattice. The coupled cavity modes were located two lattice constants (a) apart from each other to form one coupled cavity mode in a two-dimensional (2D) square lattice. The coupled cavity modes were located two lattice constants (a) apart from each other to form one coupled cavity mode in a two-dimensional (2D) square lattice. The coupled cavity modes were located two lattice constants (a) apart from each other to form one coupled cavity mode in a two-dimensional (2D) square lattice.

Quantum dot photonic crystal lasers

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Coupled cavity designs on two-dimensional square lattice photonic crystal cavities were used to demonstrate optical pumping of QD photonic crystal lasers at room temperature. Threshold pump powers of 120 and 370 µW were observed for coupled cavities including two and four defect cavities defined in optimised photonic crystals.